

## GALAXY AND STAR FORMATION UP TO $z \sim 1$

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### Abstract

Star formation history shows a gradual decline since the last 8-9 Gyr ( $z=1$ ). The bulk of present-day stellar mass and metal content was formed at redshifts lower than 2-3, which is consistent with a hierarchical scenario of galaxy formation. Observations of galaxy evolution during the last 2/3 of the Universe age could be done in great details, and provide numerous insights on the origin of the Hubble diagram. To some extent, the evolution and formation of present-day elliptical and spiral galaxies could be related to the most rapidly evolving galaxy populations at  $z \sim 1$ , namely the luminous IR galaxies and the luminous compact galaxies.

### 1 Introduction

Analysis of the age-metallicity relation in the solar neighborhood by Twarog (1980) indicated higher star formation rates in the past by factor 2-3, when the disk was from 1/3 to 1/2 of its present age. Hubble Space Telescope studies of Local Group dwarves have revealed a surprisingly large variety of evolutionary histories (see e.g. Grebel, 2000). Rapid technological developments in the last decade have opened a new era for galaxy evolution studies: galaxies can be detected at the earliest epochs of the Universe and their evolution can be directly compared in different redshift slices. Combination of nearby and distant Universe studies, is likely the best way to understand how (and when) stars and metal content were formed in the Universe.

The Canada France Redshift Survey (CFRS, Lilly et al, 1995) have probed the evolution of luminous ( $L^*$ ) galaxies up to  $z=1$ . The fraction of star forming galaxies rapidly increases with the redshift: more than 50% at  $z>0.5$  have  $W_0(OII) > 15\text{\AA}$  (Hammer et al, 1997), which should be compared to 13% locally (Zucca et al, 1998). This observed trend is followed by a variation of the average rest-frame  $(U-V)_{AB}$  color from 1.6 (Sab color) at  $z \sim 0$ , to 1.3 (Sbc color) at  $z=0.5$  and 0.7 (Sdm-Irr color) at  $z=1$ .

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## 2 Star formation history up to $z=1$

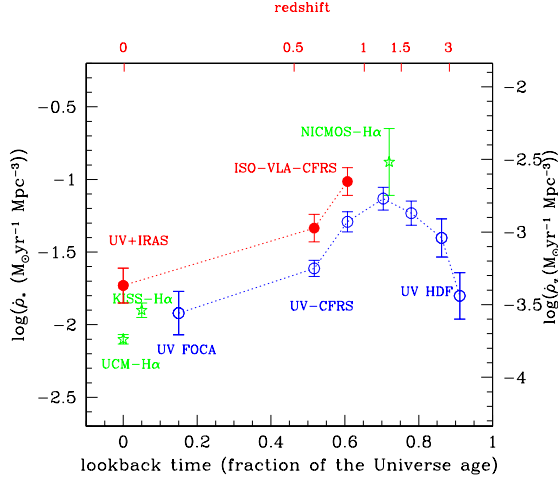
The increase in star formation with redshift has been quantitatively estimated by Lilly et al (1996) from the rest frame 2800Å luminosity, whose comoving density evolves as rapidly as  $(1+z)^{3.9\pm0.75}$ . This value is provided after assuming a constant slope of the galaxy luminosity function (GLF) in the  $[0, 1]$  redshift range. This evolutionary change has been interpreted as due to a large decrease of the star formation by a factor 10 from  $z=1$  to  $z=0$  (Madau et al, 1996). This factor could be revised downward to  $\sim 4$ , as found by Cowie et al (1999), a large part of the discrepancy being related to uncertainties on the local SFR density value.

However, optical studies of rest-frame UV light from distant galaxies do not tell us all the story. A large fraction of the UV luminosity could be absorbed by dust and then reemitted in the far IR. The effect is particularly significant for the luminous IR galaxies which dominate the upper end of the bolometric GLF. Using CFRS data, Hammer and Flores (1998) have shown that UV and [OII]3727 luminosities are not correlating with  $H\alpha$  luminosities, while they correlate well together. This suggests that extinction is a major source of uncertainty for determining the star formation history.

From a CFRS follow-up study with ISOCAM and VLA, Flores et al (1999) have provided the first estimate of the SFR density at  $z \leq 1$  which was missed by optical measurements because of dust. They conclude that 4% of the field galaxies at  $z \leq 1$  are strong and heavily extinguished starbursts with SFR from 50 to 200  $M_{\odot} yr^{-1}$ . This sparse population is responsible for almost a third of the global star formation density at  $z \sim 1$ . Assuming a non evolved IR GLF, the resulting global star formation density is  $2 \pm 0.5$  times higher than derivations from UV measurements (Figure 1). The SFR density increases by a factor ranging from 5 to 10 from the present epoch to  $z=1$ . The uncertainties related to that study are coming from: (1) those related to local values; (2) the ambiguity about the source of IR emission in some luminous galaxies (Seyfert2); (3) a possible evolution of the GLF lower end; and (4) a possible evolution of the IMF. The observed SFR density decline since  $z=1$  is mostly due to two rapidly evolving populations (Figure 2), namely the luminous IR galaxies (LIRGs, Flores et al. 1999) and the luminous compact galaxies (LCGs, Guzman et al. 1997). LIRGs are large and relatively massive starbursts often found in interacting systems. LCGs are an emerging galaxy population at  $z \geq 0.5$ , representing  $\sim 30\%$  of the galaxy population, while they have very few counterparts in the local Universe.

## 3 Testing scenarii of galaxy formation

A simple integration of the global star formation leads to the formation of half of the present-day stars since  $z=1-1.5$  (Flores et al, 1999; Madau et al, 2001; Franceschini et al, 2001). At  $z=3$ , less than a third of the present-day metal content was formed, even accounting for large dust corrections (scenario of a constant star formation density beyond  $z \sim 1$ ). This favors a scenario in which the bulk of the metal content in the Universe is formed at relatively recent epochs ( $z \leq 2$ ), supporting



**Fig. 1.** Observed metal production and star formation densities at different look-back times (from Hammer, 2000). SFR estimates are assuming a Salpeter IMF from  $0.1 M_{\odot}$  to  $100 M_{\odot}$ . Flores et al points (filled circles, labeled ISO-VLA-CFRS) show a global SFR density (contribution of both UV and IR photons), two times higher than the values previously derived from UV (open circles). Highest  $z$  estimates at rest-frame UV are from Connolly et al (1997) and from Madau et al (1996, HDF, open squares) and have not been corrected for extinction. Estimates from  $H\alpha$  luminosities (stars) are from Gallego et al (1995; UCM), Gronwall (1998; KISS), and also from few galaxies at  $z \sim 1.25$  (Yan et al, 1999; NICMOS).

a hierarchical scenario, i.e. that massive galaxies are gradually built up through the coalescence of smaller building blocks. The above considerations could challenge the assumption that all massive galaxies were formed through a primordial collapse at the earliest epochs ( $z \geq 3$ ), because most of the metal are locked into massive bulges (Fukugita et al, 1998).

When massive ellipticals (E/S0) have been formed? Bernadi et al (1998) found a tight color- $\sigma$  relation for a sample of early-type galaxies in the field as well as in galaxy clusters. Such a tightness demands a high degree of synchronicity in their star formation histories, that is naturally accounted for by pushing back to early times ( $z \geq 2$ ) most of their star formation (Bower et al, 1992; Renzini, 1999). A large fraction of massive ellipticals lie in clusters or in groups, and having most of their star formation at high redshifts could be accommodated in hierarchical models, because clusters form out of the highest peaks in the primordial density fluctuations (Kauffmann and Charlot, 1996). However, in low density environments, the model predicts much recent epochs for their star formation, including through

**Fig. 2.** (ATTACHED JPEG FILE) Example of the main contributors of the star formation history, i.e. a LCG ( $z = 0.77$ ) and a LIRG ( $z = 0.65$ ) detected by ISO. *Top* I band HST imagery. *Bottom* VLT/FORS1 spectra (3 hour exposure, Hammer et al, 2001) which reveal the important absorption line system and strong emission lines. In the Right panel, the continuum and absorption lines are well reproduced by a combination of B, A, F, and G stars (dot-dashed line, Gruel et al, in preparation).

mergers of dissipative gas rich disk galaxies. It has been suggested that ellipticals could be shared in two classes, one class comprising low to moderate mass and luminosity lenticulars and ellipticals, the other the most massive ellipticals often found in groups or clusters (Faber et al, 1997). Both classes occupy different part of the fundamental plane, and might have different star formation history. Genzel et al (2001) have suggested that ultra-luminous IR galaxies (ULIRG), which are found in merging systems, are progenitors of the less massive ellipticals. At least 20% of ellipticals could be formed during such events since  $z=1$ , according to the number density of colliding giant disks detected by ISO (e.g. Hammer, 2000). Another constraint to the epoch of field E/S0 formation is provided by their number density 8-9 Gyr ago ( $z=1$ ): it is comparable to that found locally (Schade et al, 1999), but the result is limited by small number statistics. Moreover, about 30% of morphologically selected ellipticals show signs of star formation revealed by their colors and emission lines, and could not be considered as non-evolved ellipticals as those seen today. From a recent study of 145 E/S0 at  $z \leq 1$ , Im et al (2001) rule out that more than 50% of the ellipticals can be formed since  $z=1$ . Present-day observations then suggest that from 20% to 50% of ellipticals, mostly the less massive ones, were forming the bulk of their stars at recent epochs ( $z \leq 1$ ). What is the star formation history of disk galaxies? Modelling of the Milky Way (see Boissier and Prantzos, 1999) as well as the Schmitt law for disks (Buat, 1992; Kennicutt, 1998) argue in favor of a rather long duration (3-7 Gyr) for the formation of the bulk of their stars. The density of large disks ( $r_{disk} \geq 3.2h_{50}^{-1} \text{ kpc}$ ) is found to be the same at  $z=0.75$  than locally (Lilly et al, 1998). Having most the disks already in place at  $z \sim 1$  is also supported by the apparent non-evolution of the Tully Fischer relation as reported by Vogt et al (1998). Above studies are however limited, either by model assumptions (Boissier and Prantzos model assumes no galaxy interaction), or by small number statistics (Lilly et al and Vogt et al studies) or by a somewhat unadapted observational set-up (slits not aligned to the galaxy major axis in the Vogt et al study).

Clues for a high redshift formation of disks -and then a gradual disk formation during the last 8 Gyr- have been derived on the sole basis of optical observations. Conversely to that, IR observations reveal that a noticeable fraction of disks show recent and rapid evolutions, probably because of galaxy interactions. Deep mid-IR counts show a strong evolution (Elbaz et al, 1999), mostly related to  $z \leq 1.2$  disks, often found in interacting systems. About 30% of the large disks at  $z=0.5-1$  are IR luminous, and experience strong episodes of star formation at rates of several tens

of solar mass per year, exceeding by far estimates from rest-frame UV light. It is still unknown what is the fraction of  $z \sim 1$  disks which are disrupted during merging events. Galaxy interactions and extinction related effects could also severely affect dynamical measurements such those from the Vogt et al (1997) study.

How spiral galaxies were forming ? What they look like during their early stages of formation ? Hammer et al (2001) have suggested that luminous compact galaxies (LCGs) were indeed progenitors of disks comparable or smaller to the Milky Way. LCG spectra (Figure 2) reveals strong metallic absorption lines combined with intense emission lines: their main stellar population are evolved stars with metal abundances comparable to those of Milky Way's bulge, although they are sites of intense star formations. In the Hammer et al 's interpretation, star formation was firstly occuring in bulges through merging of smaller entities often revealed by deep HST imagery, while faint surrounding extends of LCGs correspond to low surface brightness disks. LCGs are very enigmatic objects and understanding their nature needs more investigations: their sizes are similar to those of local dwarves, although they are up to one hundred times more luminous than dwarves. Their kinematics from optical emission lines revealed low velocities, suggesting low masses comparable to those of present day dwarves (Koo et al, 1995; Guzman et al, 1997), although merging and large extinctions could severely affect the interpretation.

#### 4 Conclusion

Strong events of star formation and important changes in the galaxy populations were occuring during the last 8-9 Gyr. Current or soon-coming instrumentation can provide details studies of  $z \sim 1$  galaxy properties, aiming at firmly establish the origin of the Hubble diagram. Several progresses are required to understand how galaxies were formed and to recover the universal star formation history, including (this is not an exhaustive list):

- an accurate estimate of the universal stellar mass density and its evolution from either galaxy dynamics measurements and/or a better calibration of stellar mass from near-IR luminosity measurements
- dynamical studies of a large number of merging systems in the past Universe, to investigate the nature of their by-products
- multi-wavelength analyses of star formation at all redshifts, which accurately account for dust-enshrouded star formation events
- proper measurements of gas dynamics in violent events of star formation, from measurements at far-IR rest-frame wavelengths, and/or a careful account of the selection effects related to extinction in optical measurements
- a better understanding of how stars are forming in a primordial medium, as well as improvements in modelling low metallicity stellar populations

- accurate stellar mass functions in various environments, including in low abundance medium, in powerful starbursts and in massive bulges
- a better knowledge of the Type II AGN energy output, because they significantly contribute to the upper end of the bolometric GLF.

Several of the above challenges require significant progresses related to the stellar physics. VLT has a major role to play, especially with its soon-coming instrumentation. Velocity fields of galaxies -including those in interaction- will be provided by GIRAFFE with its 3D spectroscopic mode and at intermediate resolution ( $R \geq 5000$ ,  $\delta v \sim 30$  km/s). At the focus of an 8 meter telescope and from its large multiplex, GIRAFFE will be unique for investigations of the low abundance stellar properties by observing a large number of stars up to the Magellanic Cloud and further away. Star formation histories of Local Group galaxies will be carefully analysed by measuring the metal abundance of their giant stars. Deepest spectroscopic surveys by VIMOS will provide invaluable insights of the GLF well below  $L^*$  up to  $z=1$ . After its launching, SIRTIF will be unique for determining the IR luminosity function up to large redshifts ( $z=2-3$ ), and then will firmly establish the fraction of star formation occurring in very dusty environments. Further important progresses are also expected during the next decade. At sub-mm wavelengths, ALMA will be able to detect the earliest events of dust-enshrouded star formation, because, at high redshift, the  $100 \mu\text{m}$  thermal peak progressively enters the sub-mm window, which almost compensates the cosmological dimming. It will also provide accurate measurements of the gas dynamics at sub-arcsecond scales, independently of extinction effects. At near-IR, the NGST will fully investigate the optical emission properties of highly redshifted galaxies. Further progresses are however needed for improving the spatial resolution, because 1kpc at  $z \geq 0.7$  represents  $0''.1$ , twice the resolution the NGST (diffraction limit of a 6.5m at  $2.2 \mu\text{m}$ ). Development of adaptive optics from the ground, including from multi-conjugate analyses, is a very promising way and could generate instruments for the 2nd generation at VLT. For example, FALCON could complement the NGST by studying velocity fields in distant starbursts. Such developments are a prerequisite for the next generation of extremely large telescopes (ELTs with diameters  $\geq 20$  meters). From their large collecting areas and their image quality (assumed to be restored near their diffraction limits), ELTs such as NG-CFHT, CELT or OWL, would allow a new giant step in our understanding of the distant Universe.

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